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River doctors: Learning from medicine to improve ecosystem management

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ABSTRACT

Effective ecosystem management requires a robust methodology to analyse, remedy and avoid ecosystem damage. Here we propose that the overall conceptual framework and approaches developed over millennia in medical science and practice to diagnose, cure and prevent disease can provide an excellent template. Key principles to adopt include combining well-established assessment methods with new analytical techniques and restricting both diagnosis and treatment to qualified personnel at various levels of specialization, in addition to striving for a better mechanistic understanding of ecosystem structure and functioning, as well as identifying the proximate and ultimate causes of ecosystem impairment. In addition to applying these principles, ecosystem management would much benefit from systematically embracing how medical doctors approach and interview patients, diagnose health condition, select treatments, take follow-up measures, and prevent illness. Here we translate the overall conceptual framework from medicine into environmental terms and illustrate with examples from rivers how the systematic adoption of the individual steps proven and tested in medical practice can improve ecosystem management.

1. Introduction

Human activities are now shaping the earth surface (Vitousek et al., 1997; Foley et al., 2005) to an extent that many contend a new geological epoch has begun, the Anthropocene (Zalasiewicz et al., 2010; Ruddiman et al., 2015). The accelerated transformation of earth is beginning, in turn, to threaten human society itself (Gleick and Palaniappan, 2010; Steffen et al., 2015), prompting calls for adopting sustainability principles and ecosystem stewardship (Chapin et al., 2010). These goals require an effective methodology to manage ecosystems to maintain biodiversity and ensure the continued provision of ecosystem services valued by society (Zhenga et al., 2013; Costanza et al., 2014).

Rapport (1995) pointed out that the similarities between ecosystem integrity and human health and its assessment go beyond an analogy, although this recognition has not gained strong traction. Indeed, apart from controversial discussions about whether ecosystem health is a valid scientific concept (Jax, 2010), there have been few attempts to scrutinize the degree to which principles and practices from medicine can be useful in ecosystem management. The central tenet of this paper is that much can be learned from how patients are diagnosed, treated and subsequent illness prevented, to improve the ways in which ecosystems are assessed and restored, and undesirable conditions avoided in the first place, since the fundamental methodological issues are strikingly similar. Therefore, the conceptual framework of medical health protocols holds tremendous potential to benefit ecosystem management by appropriately translating concepts and practices (e.g. Barton et al., 2015). This tenet is independent of whether one subscribes or objects to the concept of ecosystem health (Rapport et al., 1998; Simberloff, 1998; Karr, 1999; Boulton, 1999; Meyer et al., 2005; Jax, 2005). An important advantage of adopting the medical analogy is that it provides common intuitive ground of concepts and terms, which facilitates interactions among different people and disciplines participating in ecosystem management (scientists, policy makers, stakeholders etc.). Although is clear that one cannot ignore the fundamental difference between humans and ecosystems, which, for instance, neither reproduce nor die, this recognition does not invalidate the usefulness of the parallel.

Conventional medicine is the result of knowledge accumulated at least since the Greek physician Hippocrates over 2500 years ago. Nevertheless, it has only been during the last 150 years that great leaps forward have been made, with medical innovation and improvements

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rapidly accelerating at present. The success of conventional medicine lies in its systematic approach, its capacity to adopt scientific and technological innovations, its use of controlled trials and detailed case-studies as sources of evidence, and also its adherence to a suite of basic principles, along with substantial resourcing for research and patient-centered care. As we illustrate below, these points can be adapted to ecosystem management. Many have already been applied in various contexts, but we argue that substantial further benefits can be gained from systematically embracing the principles of medical practice as a whole.

Here we first identify a series of key medical principles to highlight their potential for ecosystem management. Then we illustrate how specific steps of the medical methodology (i.e. how physicians approach and interview patients, diagnose their condition, select treatments, take follow-up measures, and prevent illness) can be translated into ecosystem management. Finally, we highlight a set of treatment rules that have proven powerful in medical practice. The specific examples relating to ecosystem management that we provide are drawn from rivers to ensure a tangible and coherent account (Table 1), but we expect that the general lessons we derive are similarly applicable to other types of ecosystems.

2. Embracing medical principles

Despite the diversity of medical fields, all physicians follow a series of core principles. Six among these appear to be especially relevant for ecosystem management.

2.1. Understanding structure and function

The first principle is to base practice on a detailed understanding of the anatomy, physiology and functioning of the healthy human body. Similarly, ecosystem management is best based on mechanistic insights into the structure of ecosystems unaffected by anthropogenic pressures (i.e. their constituent elements, including organisms and abiotic factors, their spatial configuration and temporal dynamics) and into the processes that connect the individual elements. The functional dimension of ecosystems has long been ignored in river assessments, although an emerging awareness of its importance (Bunn et al., 1999; Gessner and Chauvet, 2002) increasingly leads to including functional indicators in assessment protocols (Young et al., 2008; Yates et al., 2014). The consequence of adopting these principles is that continuous investment is required to improve understanding of the structure and functioning of unaffected ecosystems that serve as benchmarks to evaluate impacts.

2.2. Identifying causes and mechanisms

A second medical principle rests on the premise that the causes and mechanisms of an illness should be understood before prescribing a cure, so the odds are high that the treatment is effective and does no harm. During much of human history, disorder and disease were erroneously interpreted as a result of agents such as evil spirits and disequilibrium in vital force (Maher, 1999; Ismail et al., 2005). Finding an effective cure on this basis was a matter of luck combined with past experience, and medical advances were slow. Today, the causes of a vast number of illnesses have been identified, including external agents such as infectious diseases or poisons, internal physiological or genetic disorders, dietary deficiencies, or disorders with mixed causes. The underlying mechanisms are often well understood at levels ranging from biochemical reactions to global epidemic outbreaks.

Similarly, changes in ecosystems can be caused by external agents (e.g. pollutants, invasive species), internal factors (e.g. natural changes in species distribution or population genetic structure) or, commonly, mixed causes (multiple stressors). Changes caused by internal factors may not be perceived as impairment, thus limiting the analogy between human bodies and ecosystems. However, since natural processes can lead to undesirable states of ecosystems, for example from a conservation or productivity point of view, the fundamental problems posed to ecosystem management and physicians in practice still remain very similar. Irrespective of the nature of ecosystem change, it is critically important for taking effective management measures to identify the proximate (e.g. excessive nutrient supply) and ultimate (e.g. climate or land-use change) factors causing a particular symptom (e.g. lack of fish or excessive algal growth).

2.3. Defining goals depending on context

Individual medical fields differ in their focus and specific goals. Routine checks involve basic techniques to detect incipient health problems and assess the general health status of a broad population. Sports medicine, in contrast, seeks to maximize physical performance in an elite group of athletes. Plastic surgery focuses on aesthetics, which may or

Table 1
A selection of parallels between medicine and river ecosystem management.

Focus	General purpose	Medicine	River management
Diagnosis	Routine examination	Body temperature, heart rate, physical examination, weight, breathing (asthma, silicosis, pneumonia…)	Water temperature, flow, river habitat survey, conductivity, oxygen deficit (ground water, organic matter…)
	Specific test	Blood examination, electrocardiogram	Detailed water chemistry, oxygen dynamics, hydrology
	Microbiological diagnostics	Microbiological analysis of pathogens	Microbiological analysis of pathogens
	Structural integrity	Radiology, physical examination	Community composition of biotic elements
	Poisoning	Toxicology	Ecotoxicology
	Risk assessment	DNA analyses for tumor screening and tumor susceptibility	Molecular community analyses to detect invasive species
Treatment	Structure restoration	Regenerative surgery	Channel restoration
	Physical elimination of problem	Tumor removal	Dam, levee or pipe removal
	Aesthetics	Plastic surgery	Landscaping
	Improvement of nutrient balance	Diet restriction	Nutrient control
	Remediative medication	Insulin injection	Liming
	Palliative treatment	Dialysis	Flushing flow releases
Prevention	Guidelines	Healthy life-style	Best management practices, sound resource management planning
	Regulation	Health and safety regulation	Environmental regulations
	Protection	Condom, sunscreen	Bio-security measures to prevent spread of invasives, waste water treatment plants
	Enhance resilience	Wound-healing drugs	Enhance river connectivity
	Enhance resistance	Vaccination	Maintenance of genetic diversity
	Education	Health education	Environmental education

may not be related to physical or psychological health issues. Regenerative medicine focuses on restoring essential body functioning in patients suffering severe damage. Finally, palliative medicine seeks to alleviate the suffering of patients with terminal illness, not to recover their health. Thus, to deal with different goals, medicine has developed different approaches and methods, all subject to equally stringent training and monitoring programs.

Ecosystem management faces strikingly parallel situations (Table 1). For instance, agencies in many parts of the world routinely monitor rivers by measuring basic chemical variables (e.g. pH, oxygen, nutrients) and determining biological community composition. Specifically adapted protocols are used in some rivers vulnerable to a particular type of chemical pollution (e.g. pesticide analyses) or receiving special protection to conserve biodiversity (e.g. assessment of pearl mussel recruitment). Similarly, restoration works reintroducing large wood and boulders in river channels with heavy machinery (Nilsson et al., 2005) are analogous to regenerative medicine, while channel reconfiguration to enhance visual appeal has parallels with aesthetic surgery. Despite these different goals, ecosystem managers tend to apply standard sets of tools, borrowed from one domain for another. For example, metrics developed for the EU Water Framework Directive (WFD), whose objective is to achieve "good ecological status" in all water bodies, are applied to rivers protected under the EU Natura 2000 network, whose goal is to preserve biodiversity in a subset of ecosystems. Clearly, maladapted methods are generally unsuccessful, suggesting that much can be gained by developing and critically evaluating specific approaches for contrasting management goals.

2.4. Developing and applying the best possible technology

A fourth principle of conventional medicine is to constantly enhance established methodology with new technology. Medical laboratories invest large amounts of money to develop and improve techniques, some of many recent examples being positron emission tomography, metabolomics or robotic surgery. Ecosystem management has also benefited from technological advances. Notable examples are large-scale analyses by remote sensing (Stumpf et al., 2012) or water quality monitoring with permanently deployed sensors, which enables fine-scale analysis of temporal trends in water quality and whole-ecosystem metabolism (e.g., Clapcott et al., 2016; Val et al., 2016).

Such technological progress notwithstanding, the tools routinely used in ecosystem management are still crude by comparison. This is partly due to incomparably smaller budgets that society is willing to invest in environmental counterparts of human health. However, the much more limited funds mobilized for environmental issues, do not invalidate the principle that constantly seeking improvement is essential to progress in the long run. Further, budgets and opportunities are likely to grow as environmental technologies improve (e.g. through radically new approaches to species surveys such as eDNA analyses; Rees et al., 2014, Goldberg et al., 2016) and environmental awareness grows, not least in the context of the burgeoning One Health approach (Uchtmann et al., 2015) that recognizes the impact of environmental conditions on human health.

2.5. Employing reliable designs

Related to the principle of developing and applying the best possible technology are the constant efforts in medicine to improve study designs. Of particular concern is the fact that medical assessments are easily misled by false positives, so that success tends to be overestimated (Dresselhaus et al., 2002). Historically, this is exemplified by the preposterous practice of blood-letting, which, although ineffective, if not detrimental, used to be extremely popular (Wootton, 2006). Approaches such as double-blind tests have been devised to preclude bias in judgement, and allowed establishment of what is known as evidence-based medicine (Sackett et al., 1997; Grol and Grimshaw, 2003).

Ecosystem management would benefit from similarly stringent procedures to evaluate remediative action (Sutherland et al., 2004, 2015), particularly by fully embracing the weight-of-evidence approach also used in risk assessment (Weed, 2005; Chapman, 2007). Regrettably, it is still not uncommon in present practice that agencies continue to invest money into ecosystem management measures that lack a sound theoretical basis or empirical supportive evidence. This needs to change. For instance, as argued by Ollero (2011), the so-called "river parks" created for conservation purposes in Spain have resulted in more environmental harm than benefit, which prompted him to call for a moratorium on action until the basics of river restoration are well understood by the authorities. A first step towards adopting the stringent medical procedures to assessments of restoration effectiveness would be to require independent accredited experts to conduct these assessments.

2.6. Relying on specifically trained personnel

A sixth principle is that medicine is practiced exclusively by specifically trained and qualified staff. Even apparently simple procedures, such as taking blood samples, are restricted to trained personnel, either medical doctors or nurses. Furthermore, there is a clear-cut distinction among the tasks that each person is allowed to perform, from the nurse to the general practitioner and specialist, and from the anesthesiologist to the surgeon. Additionally, most modern health systems have established procedures to ensure specific professional education, recognizing that continued learning is mandatory to keep up with medical advances (Schrock and Cydulka, 2006). Importantly, training must be sufficient to enable recognition not only of common but also of rare health problems. This is the reason why it is compulsory to have extensive clinical training in hospitals, where a much larger range of disorders is encountered than in a general practitioner's office.

The lesson for ecosystem management is that procedures need to be devised, implemented and enforced to train and certify professionals, as human error jeopardizes reliable assessments and treatment success (Haase et al., 2010). This includes clear definition of the functions and aptitudes of particular categories of staff, ranging from sampling and sorting to identifying organisms, and from straightforward chemical or hydrological analyses to sophisticated chemical analytics or the design of large-scale restoration projects. Defining the learning trajectory in the education of practitioners is equally important, preferably at an international level. First steps have been taken by learned societies (e.g. Ecological Society of America, Society for Freshwater Science) to establish accreditation systems based on training and certification of specialized ecologists. However, the systems in place (e.g. the Society for Freshwater Science Taxonomic Certification Program; http://www.sfstcp.com) are neither comprehensive nor legally binding. Refinement, wide application and legal establishment are needed to ensure that specialized staff perform specialized tasks. Similar to clinical training in hospitals, training would be particularly effective if it included extensive visits of case studies where specific stressors play a role and have been addressed.

3. A medicine-inspired approach to ecosystem management

Medical doctors follow a stepwise procedure to diagnose impairment, prescribe treatments and follow up the evolution of patients. This strict sequence of action can serve as a rule for ecosystem management, too.

3.1. Anamnesis

The first step in curing a disease is an accurate and precise diagnosis. Medical diagnosis starts with anamnesis, where physicians examine the medical history of patients and inquire about personal matters such as general constitution, profession and life-style before asking questions about the particular health problem. Anamnesis is a key step, as a

Box 1
Diagnosis and treatment of an impaired river ecosystem: Hypothetical Stream is a mountain stream with an abnormally low abundance of trout.

Step 1. Anamnesis
Gather information about the stream, including geology and catchment land use, and question water managers and local residents. The local angling association reports huge fish catches in the past. The Wildlife Service states that trout densities in the past were not extraordinarily high. Rangers assert that trout abundance has declined, but cannot say whether the decline had been gradual or sudden. Similar declines are not evident in other streams in the region. A dairy farm present in the catchment for over 100 years changed farming practices about 15 years ago. Other potential stressors include extensive landfills originating from mines abandoned decades ago, which have not changed over the last 20 years. There is also no evidence of a region-wide stressor, such as acid rain or pesticide use.
Step 2. Differential diagnosis
Start gathering existing information and measuring general indicator variables. Instream habitat is appropriate for trout. Local water authorities provide data on water quality and invertebrate communities, which do not indicate a problem. No change has been detected in flow regime. The riparian vegetation is intact. Based on this information, initial hypotheses are formulated about causes of the trout decline.
Analyze specific indicators with special attention given to effects of the farm (growth of filamentous algae, anoxia, etc.) and mine waste (pH, metal concentrations). Litter decomposition is slower than in similar streams nearby. Diatom communities suggest incidences of acidification and metal pollution, supporting the initial hypothesis of mining impact. The trout population is dominated by old fish. Other indicators, such as growth of benthic algae protected from grazing, are within a normal range.
Obtain information on acidification. Bioassays confirm that adult trout survive in the stream for at least 20 days. However, trout and stream sediments show elevated metal concentrations. Monitoring during rainfall events reveals episodes of low pH (<4.5) and high metal concentrations, suggesting leachate of mine waste from the landfills into the stream.
Broaden the spatial scope. Incorporate tools for differential diagnosis. The catchment upstream appears to have experienced little influence from human activity. Few changes have occurred in the last decades, except for the dairy farm. A low dam effective as a fish barrier was built 13 km downstream 16 years ago.
A diagnosis is finally reached. The periodic leaching of acidic mine waste during occasional heavy rainfall affects the trout population, although it does not cause adult fish mortality. The problem has probably been chronic for a long time, but fish re-colonizing from downstream disguised the lack of recruitment. The dam construction prevented re-colonization, and thus, the population gradually declined.
Step 3. Treatment
Address both factors supposed to have caused the trout decline. First, divert rainwater to prevent seepage of mine waste from the landfill. Secondly, re-establish longitudinal connectivity by installing a fish ladder in the dam, ensuring that juvenile trout can pass but invasive black bass in the lower reaches cannot.
Step 4. Monitoring
Monitor trout density and age structure on an annual basis for five years following the remediation measures. Establish a stream-water monitoring programme to determine whether heavy rainfall leads to acid pulses. Monitor the stream reach upstream of the

Box 1 (*continued*)
dam by bimonthly environmental DNA analyses and annual electrofishing to track whether black bass have invaded. Stock the upstream reach with young-of-the-year trout caught downstream, and set aside funds to address any upstream incursions of black bass.
Step 5. Dissemination
The diagnosis, treatment and results of the monitoring are shared worldwide in a scientific journal article and on a dedicated website (e.g. Sutherland et al., 2004).

patient's medical history can be critical to understand current symptoms, assess health risks or prevent particular therapeutic approaches (Coulehan and Block, 2005). Likewise, historical information on impaired ecosystems, such as past toxic spills, chronic pollution, species introductions, or geomorphological modifications, should be gathered to identify legacies not immediately evident. Notably, legacies can include incidences remote from the site of enquiry, because of long-distance atmospheric or river transport, thus necessitating expansion of anamnesis to whole drainage basins or potentially even larger areas. Historical environmental data tend to be limited and unreliable, which puts ecosystem managers in a position akin to that of medical doctors working in situations where a functioning medical system is lacking (e.g. in some rural areas of developing countries or regions affected by conflict). It is, nonetheless, important to gather all available information, and to be able to discern the parts that can be most relevant and reliable.

Medical interviews follow prescribed protocols with questions that go beyond the stated problems (Stoeckle and Billings, 1987). Information such as age, job and habits (smoking, alcohol consumption, participation in high-risk sports) is routinely considered to evaluate the diagnostic findings in context and to pinpoint the most likely issues. Importantly, physicians are aware that patients often provide incomplete or incorrect information, and exaggerate or play down symptoms (Nardone et al., 1992). Therefore, seemingly irrelevant questions are devised to gain contextual information, including delicate issues such as family abuse, without the patient suspecting the intention. When ecosystem managers interview stakeholders to gather information on the history and state of impaired ecosystems, the same precautions apply but are rarely recognized: stakeholders can give incomplete, partial, narrow, exaggerated, or plainly inaccurate information (Box 1). Therefore, questions must be carefully designed and responses cautiously analyzed to serve ecosystem management as well as anamnesis helps physicians in diagnosis.

3.2. Differential diagnosis

Anamnesis is followed by medical examination combining the collection of both general and specific evidence to identify likely health problems (Stoeckle and Billings, 1987). Since most symptoms can have multiple causes, the goal is to narrow down the possible origins of a problem by applying a set of criteria to distinguish between alternative diseases. This is the purpose and approach of differential diagnosis. Examinations routinely start by monitoring general variables such as body weight, heart rate and blood pressure before applying specific diagnostics. Sometimes general practitioners directly make measurements, sometimes samples (blood, urine, etc.) or the patients are sent for analyses or examinations requiring specific expertise or equipment (e.g., analytical laboratory, radiologist, cardiologist). Physicians can employ a huge diagnostic toolbox, and selecting the most meaningful tests can be challenging. Although experience and intuition play a role, accurate diagnosis is primarily a result of logical reasoning. This includes identifying the most relevant indicators, taking into account the prevalence of diseases in different sectors of society (Fig. 1A–D).

Fig. 1. Four contrasting people subject to varying medical risk factors, illustrating the parallels between prospective medical patients and potentially impaired river ecosystems. Medical doctors use the same general approach, but different sets of indicators in the diagnosis of each patient. For example, a pregnancy test would be relevant only for individual A. Similarly, although all four people could have lung cancer, the probability is much higher for individual D. All four individuals could be subject to a physical performance test, but expectations on healthy performance and future health goals would differ widely. The medical goals would also differ: top physical performance (A), relatively autonomous and painless life (B), early detection of emerging problems (C), and changing risky habits (D).

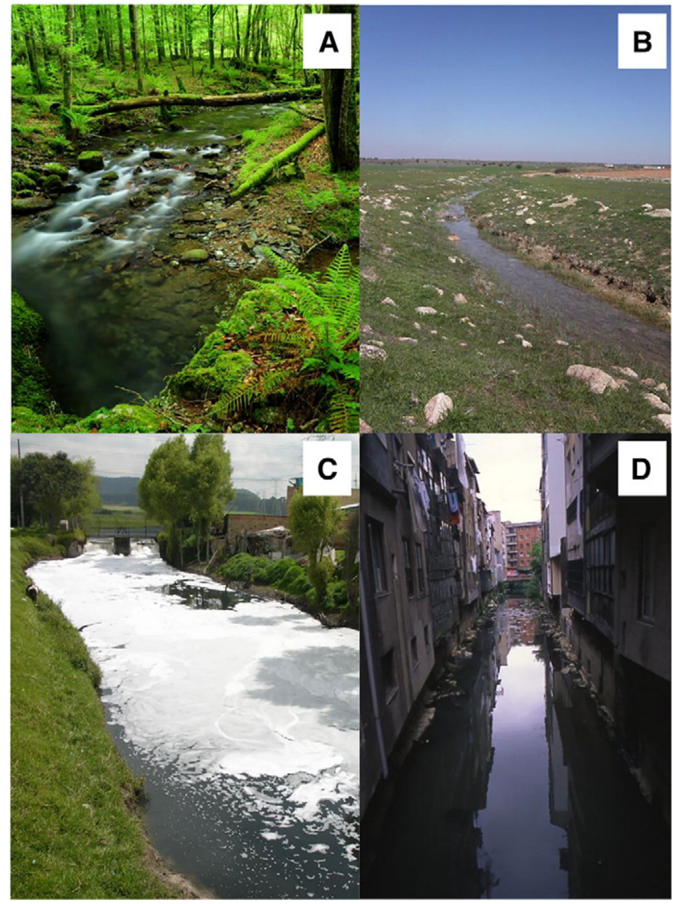

Fig. 2. Four rivers affected by different stressors. Ecosystem managers can adopt the approaches established in medicine to diagnose and treat disease, based on a set of general and specific indicators while recognizing that objectives vary among rivers. A key goal for a pristine forest stream (A) may be biodiversity conservation involving expensive measures to protect a single critically endangered species. A management priority for a river affected by deforestation and livestock grazing (B) would be to restore riparian vegetation. Water temperature, the presence of leaf-shredding invertebrates and litter decomposition rate could serve as indicators to assess success. Identifying the sources of gross river pollution indicated by a thick foam cover (C) is straightforward, but any remediative measures need to be followed by monitoring water chemistry and benthic invertebrate communities. In strongly modified urban rivers (D) options for improvement are severely restricted, and may be limited to simply meeting minimum water quality standards.

Differential diagnosis is equally applicable to ecosystems (Fig. 2), where it could be defined as a systematic approach to distinguish, based on unique sets of characteristics, between two or more potential causes of ecosystem impairment that share symptoms. Differential diagnosis starts with broad indicators and progresses using increasingly specific criteria to screen out potential causes of a problem (Box 1). A wide range of indicators has been developed. Examples for river ecosystems (Bonada et al., 2006; Woolsey et al., 2007; Friberg et al., 2011) include some with specific targets, such as diatom indices to reveal impacts of acidification (Van Dam, 1988). However, a general diagnostic framework for selecting indicators to differentiate among multiple causes of ecosystem impairment is lacking. Many indicators (e.g. macroinvertebrate community structure) have been developed to provide an integrated assessment of general ecological state, and therefore offer little diagnostic power. First steps have recently been made towards establishing a differential diagnosis approach to river assessment (Elosegi and Sabater, 2013), but clearly more development is required in theory and practice. This includes integration of both the structural and functional dimensions of ecosystem condition (Bunn and Davies, 2000; Gessner and Chauvet, 2002) in a systemic perspective.

Although most patients suffer from one of a relatively short list of diseases, such as flu or intestinal disorders, physicians are aware of the possible incidence of other and sometimes rare afflictions. Similarly, environmental stressors such as excessive nutrient loading, toxic pollution or channel modification are frequent in rivers, and hence the target of most management efforts. However, a solid understanding of a much broader range of stressors (e.g. pharmaceuticals, endocrine disruptors, various factors relating to climate change), including their prevalence and effects, is needed for accurate diagnosis in rare or complex cases.

Patients and ecosystems alike often show multiple symptoms at the same time, as reflected by the term syndrome to describe a suite of ecosystem responses to particular stressors (e.g., the urban stream syndrome; Paul and Meyer, 2001; Walsh et al., 2005). It is important to recognize these, as well as multiple-stressor situations (Townsend et al., 2008; Ormerod et al., 2010), where one stressor might reduce the effect of a remedial action to reduce damage caused by another stressor, or preclude the use of particular treatments. For instance, increasing longitudinal connectivity might be the measure of choice to alleviate the common problem of fragmented populations in river networks; however, the associated high risk of invasion by exotic species might preclude implementation of this measure. An important precaution in this context is to consider that impacts can be due to indirect effects caused by altered species interactions, which can lead to counterintuitive outcomes (Gessner and Tlili, 2016).

3.3. Treatment approaches

After reaching an accurate diagnosis, medical doctors must select among alternative treatment approaches. Some types of treatment are curative in the sense that they solve a given problem, others are palliative, meaning that damage or symptoms are only alleviated. This distinction also has evident parallels with actions taken in ecosystem management. For example, a heavily modified ecosystem could receive a treatment equivalent to palliative care (e.g. the construction of artificial pool-riffle sequences to improve habitat diversity in rivers), without restoring the ecosystem, whereas remediation of an ecosystem affected by toxic contaminants could aim for full recovery. Some treatments need to be applied just once to be effective, others are prescribed forever. Dam removal from rivers is a one-time operation, whereas stocking of juvenile fish may have to be perpetual, if conditions cannot be sufficiently improved to establish self-sustaining populations. Ecosystem management involves recognition that restoration to meet one environmental goal may limit the ability of other social, economic or environmental objectives to be met. Therefore, trade-offs between different goals and values are an inherent consideration when deciding on treatments.

Treatments can follow one of two general strategies: the causative agent such as a pathogen or environmental stressor is removed to enable recovery. This is passive restoration. Examples from rivers are the removal of livestock to let riparian forests regenerate or sewage treatment before discharge into a receiving stream. By virtue of their intrinsically dynamic and resilient nature, rivers often recover rapidly from anthropogenic impacts, and may thus serve as models to implement this approach, whereas the response of other ecosystems can be much slower. Alternatively, recovery of impacted ecosystems can be actively promoted. Examples for rivers include fish stocking, channel widening, wood and boulder additions, dam demolition to re-establish longitudinal connectivity or artificial floods to partially restore natural flow regimes (e.g. Bernhardt et al., 2005; Marks et al., 2010; Poff et al., 2010; Cross et al., 2011; Olden et al., 2014).

One important rule to select treatment approaches is to minimize unwanted side-effects. This rule encapsulates the 2500-year old Hippocratic oath as a foundation of western conventional medicine (Palmer et al., 2005). It is equally relevant in the context of ecosystem management. One example of undesirable side-effects is the detrimental compaction and disturbance of riparian soil by using heavy machinery to improve habitat structure and diversity of river floodplains. Similarly, attempts to restore longitudinal connectivity of river channels also remove barriers for invasive species, which can have detrimental effects on upstream populations of indigenous species.

Minimizing intrusion is another important point to consider when selecting treatments, and has led to great progress in medicine. Open surgery is increasingly replaced by endoscopy, broad-spectrum antibiotics by specific ones, and advances in chemotherapy have improved specific targeting of carcinogenic cells. Similarly, ecosystem management should favour methods that minimize intervention. For instance, although river bends can be dug with heavy machinery to revitalize straightened channels of formerly meandering or braided rivers, an attractive alternative is to trigger natural lateral movement of riverbeds by breaching levees, removing rip-rap and introducing large wood to initiate bank erosion (Tockner et al., 1998; Kail et al., 2007). The second, minimally intrusive option reflects natural dynamics and thus is clearly preferable in most circumstances. In addition, it is less expensive, which enables application at the same cost at larger scales, albeit over longer time periods.

Treatment selection must also consider risks and uncertainties. An incorrect diagnosis leads to an incorrect prescription and can cause harm. Therefore, medical doctors carefully weigh the risks and benefits of taking action. Even simple medical interventions like blood withdrawal involve risks. This is similarly true for most actions taken in ecosystems. For example, re-connecting river channels to their floodplain could entail property damage and even deaths during floods, or mobilize toxic chemicals stored in the floodplain. Therefore, it is essential to identify all significant risks with potential to damage humans or the environment. The ubiquity of risks has led to warnings against the overreliance on medicine to address the public health challenges of modern western society (Gigerenzer, 2013). This point clearly has parallels in ecosystem management, where large investments are sometimes made in traditional hard engineering when passive measures would be cheaper, more effective and less risky (Feld et al., 2011).

How doctors weigh risk is strongly dependent on context. When the potential benefits are large and alternatives are lacking, even measures involving high risk may be acceptable. Physicians are legally obliged to inform their patients about both the benefits and risks of a proposed treatment and any alternatives. Similarly, in the case of ecosystems, residents, agencies, industries and others possibly affected by management actions should be informed about the benefits and risks associated with a proposed intervention. This requires suitable participatory processes to ensure that the stakeholders can play a role in decisions to be taken.

Choices about medical therapy can involve triage, a contentious issue referring to the diversion of scarce resources away from patients with low recovery prospects to others with a better chance of recovery. Though ethically less delicate, defining priorities for ecosystem management efforts is often similarly controversial. Clearly, however, it can be appropriate to avoid devoting resources to situations where positive ecological outcomes will be limited (Statzner and Sperling, 1993; Statzner et al., 1997). This insight has gained recognition in several environmental policies. For example, the EU WFD defines so-called heavily modified water bodies, for which lower standards are accepted if some specified uses such as elementary human needs and drinking water supply are compromised by measures to improve ecosystem conditions.

One important factor that causes risks is uncertainty, which hence needs to be carefully considered as well. This situation is particularly familiar to hospital emergency departments, where, to prevent serious damage, immediate action may be needed before all relevant information can be gathered. Similarly, ecosystem management measures must sometimes be taken with incomplete information at hand because action cannot be delayed (Cullen, 1990; Singh, 2002). Toxic spills in rivers are an analogue of accident patients in emergency hospital departments, requiring prompt decisions. Importantly, however, uncertainties are by no means restricted to emergency situations but are commonly due to ambiguous diagnostic outcomes or even failure to diagnose any particular problem. To minimize risks, it is crucial in all of these situations involving uncertainties that sound protocols are established to guide decisions – as much for impacted ecosystems (Schindler and Hilborn, 2015) as for medical patients.

3.4. Monitor response to therapy and adapt treatment accordingly

Medical advances only started speeding up when the scientific method was fully embraced. This includes patient surveillance following treatment. One alarmingly weak feature of ecosystem management practices in general, and river restoration in particular, is the lack of adequate monitoring (Jähnig et al., 2011; Bernhardt et al., 2005; Palmer et al., 2005). Clearly, monitoring is an indispensable component of ecosystem management, particularly after restoration measures have been taken, and investing the necessary funds to implement a monitoring scheme is thus imperative. Given that financial resources are nearly always limiting, this may involve accepting a reduction in the desired scope of a particular restoration measure for the sake of properly following up on the results and reserving contingency funds for adaptive measures if unanticipated negative consequences arise.

Adaptive ecosystem management has arisen as an approach to make decisions in the face of uncertainty and recognizes the need for robust monitoring to determine the success of alternative management actions and support future decision making (Holling, 1978). While showing much promise, attempts to implement adaptive management often suffer, however, from problems with the associated monitoring programs, as well as from a lack of connection with stakeholders (Greig et al., 2013).

3.5. Widely publicize treatment outcomes

Clinical research has achieved a high level of internationalization. Large-scale studies are conducted in multiple nations to boost sample sizes when disease prevalence is low, and there is considerable pressure and incentives to disseminate results to the broad medical community. This includes reporting both positive and negative outcomes to limit publication bias. Importantly, the international dimension of major clinical trials often goes beyond communicating results in the technical literature and also includes targeted dissemination of information to practitioners.

Given limited communication, most ecosystem restoration projects go unnoticed beyond a small geographic range. This prevents knowledge transfer and thus obliges others to learn from their own experience and mistakes. Consequently, embracing the duty to inform others about the outcomes of management measures as a principle is likely to propel progress in ecosystem management. A critical point is to avoid bias towards successful projects (Jähnig et al., 2011). Failures are often equally instructive, as they can point to important misconceptions (Bernhardt and Palmer, 2011). Although an effective communication system could be put in place in various ways, a system that involves both incentives and pressure is likely to be needed to promote wide commitment of the community.

3.6. Further prevention

With the causes and mechanisms of action identified for many diseases, methods have been devised to prevent the risk of suffering from specific diseases. The same is true for ecosystems, as knowledge grows about the causes of stressors and poor ecosystem conditions. The importance of preventing excessive nutrient supply and the spread of invasive species is widely recognized in ecosystem management. Nevertheless, policy makers and ecosystem managers often repeat mistakes in different places and contexts, as a consequence of a lack of either knowledge or political will. For instance, the introduction of exotic species for various reasons, such as landscape restoration or sport angling, has caused not only ecological harm but also huge economic loss (Pimentel et al., 2005).

Despite the value of the precautionary principle, complete risk prevention is not only impossible, but sometimes unwise. Opportunity costs must be taken into account to avoid spending resources in situations where marginal benefits are the best possible outcome (Statzner et al., 1997). Preventive measures are often taken by the medical community at a very broad spatial scale, such as when a risk of pandemics has triggered measures to limit the movement of goods or people (Stein, 2015). Clearly, prevention does not necessarily work at the individual level alone. This lesson can be transferred to ecosystem management where preventive measures should consider the broader landscape. For rivers, this includes the floodplain, river network, catchment and even larger geographical units, including earth as a whole.

Information alone cannot prevent all issues. People aware of the habits and attitudes that promote health (e.g. healthy food, exercise, no smoking) may ignore them for many reasons. Similarly, people aware of environmentally friendly habits and attitudes often ignore or struggle to apply them, although well-informed individuals tend to adopt healthier and more environmentally friendly behaviours (Silles, 2009; Coertjens et al., 2010). This suggests that, apart from legal measures, education can be effective at overcoming tendencies to ignore disease and environmental risks and thus enhance both public health and ecosystem stewardship. Examples of this include the steady decline in cigarette smoking and the more widespread adoption of safe driving behaviour by road users over the last decades. Striking examples for river ecosystems are the growing awareness and political drive to remove dams (Marks et al., 2010), re-establish natural flow regimes (Poff et al., 2010; Olden et al., 2014) and restore floodplain connectivity instead of relying on hard channel engineering for flood protection (Tockner et al., 1998). Similarly, environmental education campaigns have been effective in helping constrain the spread of invasive species (e.g. *Didymosphenia geminata*; Root and O'Reilly, 2012). Clearly, however, there is still much to improve in terms of risk prevention in ecosystem management.

4. Limitations of the medical template

As we have illustrated by numerous examples, there is a wide range of parallels between medicine and ecosystem management and there are many medical principles and practices that could benefit ecosystem management. However, like any analogy, the similarities can only be taken so far. In particular, the challenge of ecosystem management is often described as a so-called 'wicked problem' (Brown et al., 2010) requiring collective action from different sectors of the community to define the problem and seek solutions that are often case-specific. Appropriate therapies are easily identified in some cases, but social, economic or financial constraints complicate the implementation, especially when action is required at large scale. Different sectors of the community often have differing values and their goals are often competing and may change over time. Therefore, it is often not a simple matter of treating one issue in the absence of any consideration about other requirements of the system. This contrasts with medical practice where maintenance and improvement of human health is a common goal that is widely held, although it can also be constrained by finances, competing views among different medical specialty areas, or complications caused by changing levels of health care expectations.

5. Conclusion

To conclude, the immense successes of medical practice indicate that a sound mechanistic understanding of ecosystem structure, function, and the consequences of human stressors is important for effective ecosystem management. This understanding must be combined with a systematic application of a comprehensive toolbox for environmental assessment, including anamnesis and tools for differential diagnosis to remediate environmental problems effectively. As this toolbox becomes more complex, a broad array of specific professional skills is necessary to maximize success and prevent unwanted side effects. Effective training and information exchange among practitioners and stakeholders are hence important ingredients of success when applying principles of medical practices to ecosystem management. While our illustrations of parallels between medicine and ecosystem management is focused on rivers, we expect that the conclusions drawn are applicable to ecosystem management in general. It is time that maintaining and improving ecosystem conditions is accepted as a moral goal for humanity, as well as a necessity for achieving a sustainable future. Consequently, it must be undertaken with similar effort and diligence as efforts to maintain and improve human health, notwithstanding the greater difficulty to raise the required funds for environmental purposes. Indeed, thoughtful ecosystem stewardship can have ramifications well beyond the conservation and restoration of ecosystems, including positive feedbacks to the health and well-being of present and future generations (Messer et al., 2014; Uchtmann et al., 2015).

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